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Permanently dispelling a myth of photovoltaics via the adoption of a new net energy indicator

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Abstract

For many years, the photovoltaics (PV) community has relied on the concept of energy payback time (EPT) as a means of quantifying the ratio of energy generated from a PV panel or system over its lifetime, compared to the energy that was required to fabricate it. Few other energy technologies are so judged and this paper argues that the EPT concept is obsolete, misleading and may possibly even contribute to keeping the myth alive, that 'That PV does not payback the energy used to create it'. Therefore, a new norm for the PV community is proposed, the energy yield ratio (EYR), as used by Gürzenich et al. (Int J Life Cycle Assess 1999; 4(3): 144–9). EYR values for three different PV products (a single multicrystalline silicon module, 2 kW rooftop grid-connected system, and a solar home system) are determined to be 4.8–13.9, many times the energy inputs required to fabricate the system.

Keywords: Energy yield ratio; Energy payback time; Photovoltaics; Solar cells

Contents

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1. Introduction

The most common myth about photovoltaics (PV), often raised in community meetings, cited by the fossil-fuel and nuclear industries and making regular appearances in internet newsgroups, is 'that PV does not payback the energy used to create it'. And indeed, there are still reports of a popular belief that PV systems cannot payback their energy investment [1,2]. While this may have been an accurate statement during the first years of terrestrial PV, in this paper the authors demonstrate that it has clearly not been the case for nearly the last three decades and that it is time both to dispel the myth and to stop using terminology, which serves to perpetuate it.

The most commonly used parameter to quantify the life-cycle performance of PV is the energy payback time (EPT), defined as the time (in years) in which the energy input during the module life-cycle is compensated by electricity generated by the PV module. Naturally, the EPT depends on several factors, including cell technology, PV system application and irradiation [1]. The formulation of the EPT (with the units of years, y) in terms of primary energy (PE) as given by Kato [3] appears as

$$\mathrm{EPT} = \frac{E_{\mathrm{input}}}{E_{\mathrm{gen}}}, \tag{1}$$

with

E_{input}	PE requirement during module life-cycle (units of MJ) $= E_{\mathrm{man}} + E_{\mathrm{trans}} + E_{\mathrm{inst}} + E_{\mathrm{use}} + E_{\mathrm{decomm}}$
E_{man}	PE requirement during module manufacturing including resource mining
E_{trans}	PE requirement during material and module transportation
E_{inst}	PE requirement during module installation
E_{use}	PE requirement during module operation
E_{decomm}	PE requirement during module decommissioning
E_{gen}	PE savings due to annual energy generation by PV module (units of MJ/y).

Here, it is important to distinguish between using PE rather than electricity, as the efficiency of generating electricity varies around the world and by technology—the efficiency from a coal-fired power station is typically about 35%.

The important quantity, which is not included in an EPT calculation, is the lifetime of the PV module, L_{PV}. We argue that absence of this piece of critical information can lead to misrepresentation of the value of PV. Furthermore, the authors argue that the concept of EPT, in itself, has helped to perpetuate the myth of energy recovery. In addition, to set the record straight, a new norm for the PV community is proposed, the energy yield ratio (EYR) [4] and the EYR values for several different PV technologies and systems are calculated.

2. History of energy payback times

In 1972, one year before the birth of the terrestrial PV industry, the possibility of using PV for addressing some of the impending energy problems on earth was addressed by Wolf [5]. PV cells designed for space use had proven to be extremely successful and, considering the immense cost of the space programme and the lack of options for generating electricity in such an environment, price and EPT were not a consideration. In fact, Wolf states, firstly, that these solar cells were manufactured during a time of energy abundance on earth and the recovery of the energy spent during fabrication was not of interest, and, secondly, that the production capacity was small, estimated at 50 kW [5]. The analysis assumed the use of low-cost solar cells (4 cm^2 in size) with an efficiency (η) of 7% under AM1 illumination, which was foreseen as being readily achievable in the near future with multicrystalline (mc-Si) silicon solar cells. The EPT of these solar cells operating under terrestrial insolation was determined to be 40 y [5]. In contrast, silicon solar cells with $\eta = 18\%$ used to power a satellite (no storage required) had an estimated EPT of just 4 y.

In a subsequent paper published in 1974 Iles [6] reported a 'debt-time', which can be regarded as an EPT, for a range of space and terrestrial cells (not total systems), fabricated from monocrystalline (c-Si) and mc-Si. The EPTs for 11% c-Si space cells were 2.1 and 0.7 y for 4 and 12 cm^2 solar cells, respectively. Terrestrial devices made from c-Si had an EPT of 3.05 y ($\eta = 10\%$, 20 cm^2), while the first mc-Si solar cells (50 cm^2) had longer payback times of 5.1 and 10.2 y, for $\eta = 1$ and 2% devices, respectively.

In 1976, three works examined the EPT of c-Si solar cells. Firstly, Slesser and Hounam [7] cite a 2 y EPT for solar cells with an expected lifetime of 20 y. Secondly, an in-depth study performed by Hunt [8] showed an EPT for terrestrial PV cells of 11.6 y for 2″-diameter (~20 cm^2) devices with an efficiency of 12% under AM1 illumination, fabricated with a yield of 18%. Notably, the smaller 4 cm^2 solar cells for space application, of the type which had previously been analysed by Wolf [5], had an EPT of 24.1 y, more than double that of terrestrial cells, primarily due to even lower yields of 7.5% [8]. Yields were a major focus of the third paper, where the yield range of 50–90% was investigated for solar cells manufactured on three different wafer sizes (35, 50 and 70 mm) over a wide range of solar radiation conditions [9]. For 50-mm diameter c-Si solar cells with $\eta = 10\%$ and operating under 1825 kW h/m^2/y insolation, the EPT decreased from 21 to 11.5 y as the yield increased from 50 to 90%. However, a much longer EPT of 44 y was calculated for smaller diameter (35 mm) wafers being manufactured at low yields (50%) operating under poor solar insolation (1095 kW h/m^2/y).

By the late 1970s, further in-depth studies performed by Solarex Corporation noted that terrestrial PV flat plate technology (with an efficiency of 12.5%) had succeeded in reducing the EPT by almost an order of magnitude to 6.4 y (at the average US location), and as low as 3.8 y in the best US locations [10,11]. In addition, it was noted that the lifetime of a terrestrial PV panel could not be accurately determined due to the infancy of the industry. However, mean time between failure (MTBF) data at Solarex (at 90% confidence level) led to an estimate that $L_{PV} > 40$ y [11]. The encouraging EPT values achieved by Solarex led to the first attempt at constructing a Solar Breeder—a solarpowered PV manufacturing plant that produces net energy in the form of solar panels, first proposed by Slesser and Hounam [7]. The Solarex factory in Frederick, USA, was built with a large PV roof, one of the first applications of this type [11,12].

In the 1980s, two further studies reported on the EPT of c-Si PV modules with aluminium (Al) frames. Firstly, a Siemens study determined that their Czochralski (CZ) silicon PV modules had an EPT of 7.9 y, while the use of edge-defined film growth (EFG) silicon drastically reduced this figure to 1.6 y [13]. Hay et al. found that CZ silicon solar cells encapsulated in Al-framed modules had an EPT of about 10 y with the equivalent of 5 kW h/day at AM1 illumination [14]. In addition, these authors observed that PV modules are unlikely to ever have an EPT of much less than 1 y, which made a lifetime of at least 10 y ($L_{PV} > 10$ y) imperative, as this was regarded as the minimum for an economically viable electricity generating system [14]. As well as the c-Si baseline case, this study also included ribbon silicon, amorphous silicon (a-Si) modules and cadmium sulphide (Cu_2S):copper sulphide (Cu_2S) heterojunction modules, with both thin film technologies having an assumed efficiency of 10% and 10 y lifetime. The EPT of the ribbon Si, CdS:Cu_2S and a-Si technologies were predicted to be 5, 0.9 and 0.6 y, respectively, using the same assumptions and illumination as the CZ Si cells [14].

In the late 1980s and early 1990s, Hagedorn thoroughly investigated the potential hidden energy costs of 300 kW_p PV power stations [15–17]. Using c-Si solar panels (most likely with Al-frames) manufactured in Germany in that time, the EPT for the PV central power station was 7.2 y, while the use of a-Si reduced this figure to 4.7 y.

Since that time, there have been many improvements in PV cell and module production and performance and a range of excellent studies have been performed on calculating the EPT of many different PV technologies. Many of the current EPT studies include more realistic operation of PV modules in the field, where standard testing conditions (STC) are often not present. Apart from losses due to non-standard conditions (variable insolation, variable panel temperatures), losses in the balance of systems (BOS) equipment (inverter, transformer, cables, and possibly batteries) should be taken into account [18]. It is common practice to bundle all of these losses into a single parameter, the performance ratio (PR), which typically ranges from 75 to 81%.

The majority (62%) of PV modules fabricated in 2003 used mc-Si wafers, and gridconnected residential or commercial systems represent the largest market (51%) [20]. Recent studies illustrate the technical improvements, which continue to occur. For a 3 kW_p rooftop-mounted on-grid residential system in 2000, operating under 1700 kW h/m^2/y insolation with a PR of 75% and using 13% mc-Si PV modules, the EPT was 3.2 y [21,22]. This figure allowed for the aluminium framing for the modules, a 3 kW inverter and the array support structure. For 7% a-Si thin film modules, the EPT was even lower at 2.7 y. For a ground-mounted system, the higher BOS costs of the support structure increase the EPT for both mc-Si and a-Si technologies to 3.9 y. The EPT of other thin film technologies such as cadmium telluride (CdTe) and copper indium diselenide (CIS) have been calculated as being 1.7 y [1] (for an assumed production capacity of 10 MW of 10.3% efficient modules operating under 1430 kW h/m^2/y insolation) and 1.8 y [23] (for a 9.4% efficient 40 W_p CIS module operating under 1700 kW h/m^2/y insolation), respectively.

The worst EPT times are now for stand-alone (off-grid) PV systems that require battery storage. For a solar home system (SHS) using a single 50 W_p mc-Si module with a 70 Ah battery, the EPT ranges from 8 to 11 y for a module efficiency of 12.1–13.8%, respectively [24]. In this scenario, the BOS components contribute 50–75% to the final EPT. This analysis is performed for 1900 kW h/m^2/y insolation, as it typical in many countries where SHS are being installed, and allows for a 4 y battery life, so that five battery sets are required over the 20 y system life.

Therefore, even in the most extreme cases where other BOS components need to be regularly replaced, there is no question as to whether any kinds of PV installation will payback the energy used in its fabrication.

3. So what is wrong with EPT?

In the authors' opinion, the EPT concept has several disadvantages, as outlined below.

1. The term EPT is outdated, and would appear to have its origins in the early days of terrestrial PV where it is possible that a module may have generated less energy over its (then unknown) lifetime, than went into its production. Indeed, the mere acronym in itself implies the possibility that the product may not recover its embodied energy. In this regard, one could argue that the concept of EPT helps perpetuate the myth that has haunted PV for nearly the last three decades.
2. EPT does not reflect the life of the product. For example, while an a-Si PV module might have a better EPT than a mc-Si PV module, the latter might have a longer expected life (or at least warranty) than the a-Si product. In this scenario, the customer who is quoted an EPT is none-the-wiser as to which PV panel may actually generate more net energy over its operating life.
3. While the concept of EPT has been applied to other energy systems or products, it has not been such a contentious issue as for PV. As PV takes its place in the range of energy system options, it will be increasingly important to report on its performance, using methodologies and terminology common to the energy sector generally. Life-cycle analysis has standardised methodologies and can be used for calculating energy requirements for manufacturing, usage and disposal, for carbon dioxide impacts or for economic analysis. Such standardised methodologies allow comparison with other energy technologies and hence provide a more meaningful result than EPT.
4. The use of EPT as a net energy indicator for an entire PV system, which includes an inverter, batteries, and mounting frames, is less obvious. For example, if an end-user knows what the expected EPT of such a system is, when it is installed, then how should that person interpret any change in EPT when the battery bank needs replacing after 7 y? There are other net energy indicators, as will be discussed later, that are calculated using the expected life of each system component, and the end-user can rest relatively assured that the system remains still on target, despite replacing the battery bank. Of course, the lifetimes of each component can be provided to the user as information pieces of information, however, if we seek to redefine one parameter or number that will subtly alter the manner with which people regard PV systems then there are better indicators to use than EPT.
5. In addition, the EYR is also a better way of describing systems where different components may need to be replaced several times over the life of the whole system. While EPT can accommodate this, it requires more explanation.
6. As noted by Nieuwlaar and Alsema [25], use of EPT as an indicator of energy performance may be appealing due, firstly, to its similarity with economic payback times, however, the drawback is that EPT does not account for additional energy generated during the remainder of the economic lifetime. Secondly, the fact that additional energy inputs can simply be added is another advantage of this indicator (see further below).

4. Alternative energy indicators

Many different indicators have been used for quantifying the net energy generated by a PV module (or system) over its operating life. Terms that have appeared in the literature are outlined below, along with comments from the authors as to their applicability. It should be noted that since there are only two possible ways to calculate the ratio of E_{input} and E_{gen}—with one as either the numerator and the other as the denominator—these indicators differ primarily in name only.

- The *energy payback ratio*, as used by NASA [26] and the wider energy community [27], is too similar to EPT and may confuse the issue even more.
- *Energy ratio*, was used by Hynes et al. in their analysis of CIS solar cells [28], however, this term is somewhat non-descript. This term was also used in a report by Environmental Resources Management [29].
- The terms *net energy* [30], *energy gain* [6] and *net energy yield* [22] would suggest that these indicators should have units of energy. However, they do not have the units of kW h, while such an absolute value would still be meaningless to the majority of people.
- *Energy harvest ratio* was mentioned by Canada [31] and is a useful definition, however, the authors are not particularly fond of the horticultural analogy—we are not growing anything, and would not want to fuel any other misconceptions about the performance of a PV system throughout the seasons.
- The use of the indicator *energy return factor* (ERF) has been suggested by Niuewlaar and Alsema [25] as an indicator that combines EPT with the economic payback time. The ERF expresses the total amount of energy saved per unit energy invested and is defined as

$$\text{ERF} = \frac{E_{\text{gen}} L_{\text{econ}}}{E_{\text{input}}}, \tag{2}$$

  where L_{econ} represents the economic lifetime. Niuewlaar and Alsema [25] noted that a disadvantage of the ERF indicator is that it is not additive—in other words, ERF values of different system components cannot be added to obtain the ERF of the total system. In addition, the use of the word 'economic' may also confuse the issue further.
- The *energy production efficiency* $\eta(t)$ was introduced by Keoleian and Lewis [32] in order to introduce end-of-life management energy expenditure to the EPT. However, the EPT typically includes the decommissioning energy already (see Eq. (1)) and therefore the energy production efficiency appears as the inverse of the EPT,

$$\eta(t) = \frac{E_{\text{gen}}}{E_{\text{input}}}. \tag{3}$$

- The final indicator presented here, the energy yield ratio [1] is the authors' choice for a new term to replace the EPT and will be discussed in more detail below.

5. Energy yield ratio

The EYR has been used to assess the energy balance of PV [4] and other renewable energy technologies, such as solar hot water [4] and wind [4,33]. For a PV system, the EYR

is defined as

$$\mathrm{EYR} = \frac{E_{\mathrm{gen}} L_{\mathrm{PV}}}{E_{\mathrm{input}}}, \tag{4}$$

where L_{PV} is taken as the design lifetime of the system, often chosen to match the PV module warranty of 10–30 y, which is equal to or longer than the life of other system components.

The EYR is defined as 'how many times the energy invested is returned or paid back by the system in its entire life' [33]. This indicator is quite elegant in that an energy product with an EYR of greater than unity generates more energy over its lifetime than was required to fabricate it, while a system with an EYR of less than unity can be regarded as environmentally unsustainable. In this regard, unity is established as the break-even point, and, above that, the higher the EYR the better. In addition, the EYR is also a better way of describing systems where different components may need to be replaced several times over the life of the whole system. While EPT can accommodate this, it requires more explanation.

The EYR for a multi-component system can be expressed as

$$\begin{aligned} \mathrm{EYR}_{\mathrm{system}} &= \frac{E_{\mathrm{gen}} L_{\mathrm{system}}}{\sum_{i=1}^{n} \left(E_{\mathrm{input}(i)} \frac{L_{\mathrm{system}}}{L_i}\right)} \text{for sytem components } i = 1 \text{ to } n \\ &= \frac{E_{\mathrm{gen}} L_{\mathrm{system}}}{\left[\left(E_{\mathrm{input(PV)}} \frac{L_{\mathrm{system}}}{L_{\mathrm{PV}}}\right) + \left(E_{\mathrm{input(inv)}} \frac{L_{\mathrm{system}}}{L_{\mathrm{inv}}}\right) + \left(E_{\mathrm{input(batt)}} \frac{L_{\mathrm{system}}}{L_{\mathrm{batt}}}\right)\right]}, \end{aligned} \tag{5}$$

for the three main components in a PV system—PV panels, inverter and batteries. It should be noted that the addition of energy inputs from several components is slightly more cumbersome than with EPT.

6. Energy yield ratios of three scenarios

Based on a previous study by one of the authors [34,35] we will now calculate the EYR for three scenarios. Scenario 1, is simply a mc-Si module with $\eta = 13\%$ with aluminium frames, front glass and Tedlar rear encapsulation, and a cell packing density of 95%. In Scenario 2, a 2 kW$_{\mathrm{p}}$ (36 module, 16.2 m^2) grid-connected PV array of the same mc-Si modules is installed on the roof of a house and connected to the mains supply via a 2.5 kW inverter (with an average efficiency of 95%). And finally, Scenario 3 is a simple model of a SHS, consisting of a single 50 W$_{\mathrm{p}}$ mc-Si module, and a 70 Ah lead-acid battery (nearly 2 days worth of storage) with an in–out efficiency of 85% and maximum depth of discharge of 50%. For Scenarios 1 and 2, the PV modules are assumed to be operating either under a typical Australian insolation level of 1825 kW h/m^2/y or a typical Central Northern European insolation level of 1000 kW h/m^2/y and displacing typical Australian grid electricity generated from coal at 35% efficiency. The SHS in Scenario 3 is only considered for operation under the higher insolation level and displacing diesel generation at 16% efficiency [34,35]. A PR of 80% for the PV module is used for all scenarios, while the inverter and battery efficiencies are taken into account in Scenarios 2 and 3, respectively. The system lifetime is assumed to be either 20 or 30 y, a commonly available warranty period for silicon PV panels, while the inverter and batteries have a 10 and 5 y lifetime, respectively. The energy requirement for the battery is assumed to be

$E_{input(batt)} = 0.9\,MJ/Wh$, as used by Alsema et al. [24] and any potential benefits from recycling are not taken into account.

Using Eqs. (1) and (5), the EPT and EYR were calculated for the three scenarios and the results are presented in Table 1, while the EYR results are compared graphically in Fig. 1. The EPT values calculated here are in good agreement with the results of other research [21,22], and it is clear that all systems are able to payback the energy used in their creation within a period of 2.2–7.2 y. This is also seen in the EYR results, where the values are 2.8–13.9 times greater than the breakeven value of unity, plotted in Fig. 1. The benefit of using the EYR indicator is demonstrated by the difference in the 20 and 30 y results. Due to the PV panel not having to be replaced during this period, the EYR increases considerably in the 30 y case. Use of EPT would not convey this information. In Scenario 1, the EYR_{30} is 13.9, while this reduces slightly in Scenario 2 due to the 10 y assumed lifetime of the inverter and the necessary mounting frames. In Scenario 3, the difference between the 20 and 30 y EYR results is reduced due to the energy impacts of replacing the battery every 5 y, plus the additional mounting requirements of a ground-based system.

Table 1
Calculated EPT and EYR (over both a 20 and 30 y period) for the three scenarios considered, under both Australian and Northern European isolation levels

	Australian Insolation ($1825\,kW\,h/m^2/yr$)			Northern European insolation ($1000\,kW\,h/m^2/yr$)		
	EPT (y)	EYR_{20}	EYR_{30}	EPT (y)	EYR_{20}	EYR_{30}
Scenario 1: mc-Si module	2.2	9.3	13.9	3.9	5.1	7.6
Scenario 2: $2\,kW_p$ rooftopmounted on-grid system	2.7	7.5	11.2	4.9	4.1	6.2
Scenario 3: $50\,W_p$ solar home system (off-grid)	4.5	5.1	6.0	7.2	2.8	3.3

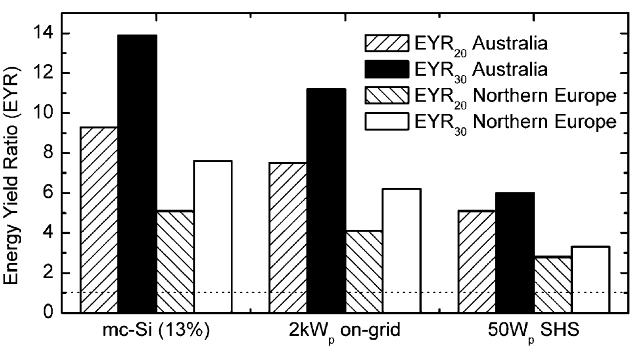

Fig. 1. Comparison of EYR results for a single mc-Si module (Scenario 1), a $2\,W_p$ rooftop grid-connected system (Scenario 2) and a $50\,W_p$ SHS (Scenario 3) operating under typical Australian or Northern European insolation levels. To break even, an EYR of unity is required, and this is also plotted on the graph.

The inappropriateness of the EPT indicator in today's PV market is perhaps best exemplified by a worst case scenario, where a monocrystalline silicon PV module operating in Northern Europe has an EPT of 6.6 y [36], however, this is less than a third of the expected lifetime of the module.

7. Conclusions

In 1973, the first terrestrial PV systems were being installed using solar cells developed for the space industry. During this brief period, EPT values of greater than their expected lifetime of the PV devices were encountered due to many different factors including that

- due to the lack of alternatives, the space industry had not been interested in the cost or energy required to fabricate their devices;
- both the physical size of devices and the production capacity were small;
- the efficiency of these early devices was low; and
- production yields were low.

Since this period, the PV community and its opponents have used the EPT indicator as a means of quantifying the ratio of energy generated from a PV panel or system over its lifetime, compared to the energy that was required to fabricate it. In this paper, we have demonstrated that PV systems have more than paid back their production energy since about 1974—one year after the establishment of the terrestrial PV industry.

The authors suggest that the EPT concept is obsolete, misleading and—even worse—may be assisting to keep the myth alive: 'That PV does not payback the energy used to create it'. Therefore, the authors have examined other energy indicators, and suggest that the EYR, apparently first used by Gürzenich et al. [1], be used as a new norm for the PV community. This net energy indicator is more elegant than the EPT since it incorporates the system lifetime and since an energy product with an EYR of greater than unity is immediately recognisable as being able to generate more energy over its lifetime than was required to fabricate it, while a system with an EYR of less than unity can be regarded as environmentally unsustainable. The EYR is also a better way of describing systems where different components may need to be replaced several times over the life of the whole system. EYR values for three different PV products (a mc-Si module, 2 kW_p rooftop gridconnected system, and a 50 W_p SHS) are determined to be 2.8–13.9, indicating that PV can truly be a sustainable long term energy solution.

References

[1] Nieuwlaar E, Alsema EA. PV power systems and the environment: results of an expert workshop. Prog Photovoltaics 1998;6(2):87–90.
[2] Kazmerski LL. Photovoltaics—exploding the myths. Renewable Energy World 2002;5(4):174–83.
[3] Kato K. Energy resource saving and reduction in GHG emissions by PV technology—values in the present and added value in the future. IEA PVPS Task I workshop on the added value of PV Systems, Glasgow 5 May 2000, p. 10.
[4] Gürzenich D, Mathur J, Wagner HJ, Bansal NK. Cumulative energy demand of selected renewable energy technologies. Int J Life Cycle Assess 1999;4(3):144–9.

[5] Wolf M. Cost goals for silicon solar arrays for large scale terrestrial applications. Proceedings of the ninth IEEE photovoltaics specialists society 1972 p. 342–50.
[6] Iles PA. Energy economics in solar cell processing. Proceedings of the symposium on the material science aspects of thin film systems for solar energy conversion 1974 p. 37–48.
[7] Slesser M, Hounam I. Solar energy breeders. Nature 1976;262(5566):244–5.
[8] Hunt LP. Total energy use in the production of silicon solar cells from raw materials to finished product. Proceedings of the 12th IEEE photovoltaics specialists conference 1976 p. 347–52.
[9] Bhaskararao A, Narahari S. Energy budget of single crystal silicon solar cells with the present state-of-art. In: Deb S, editor. Proceedings of the national solar energy convention, 1976. p. 71–4.
[10] Lindmayer J, Wihl M, Scheinine A. Energy requirement for the production of silicon solar arrays. Report SX/111/3. Rockville, MD, USA: Solarex Corporation; 1977. October.
[11] Wihl M, Scheinine A. Analysis and simulation of the energy source of the future: the solar breeder. Proceedings of the 13th IEEE photovoltaics specialists conference 1978 p. 908–10.
[12] Lindmayer J. The solar breeder. Proceedings of the photovoltaic solar energy conference 1977 p. 825–35.
[13] Aulich H, Schulze F, Strake B. Energy pay-back time for crystalline silicon photovoltaic modules using new technologies. Proceedings of the 18th IEEE photovoltaics specialists conference 1985 p. 1213–8.
[14] Hay K, Harrison JDL, Hill R, Riaz T. Comparison of solar cell production technologies through their economic impact on society. Proceedings of the 15th IEEE photovoltaic specialists conference 1981 p. 267–72.
[15] Hagedorn G. Hidden energy in solar cells and photovoltaic power stations. Proceedings of the ninth E.C. photovoltaic solar energy conference 1989 p. 542–5.
[16] Schaefer H, Hagedorn G. Hidden energy and correlated environmental characteristics of PV power stations. Renewable Energy 1992;2(2):159–66.
[17] Hagedorn G, Hellriegel E. Environmental impact studies using photovoltaics as an example. Part 5. The environmentally relevant materials in the preparation of different solar cells. Ber. Forschungszent. Juelich (Juel-2636), 1992, p. 238.
[18] Voorspools KR, Brouwers EA, D'haeseleer D. Energy content and indirect greenhouse gas emissions embedded in 'emission-free' power plants: results for the low countries. Appl Energy 2000;67:307–30.
[20] Alsema EA. Energy pay-back time and CO_2 emissions of PV systems. Prog Photovoltaics 2000;8(1):17–25.
[21] Alsema EA, Nieuwlaar E. Energy viability of photovoltaic systems. Energy Policy 2000;28(14):999–1010.
[22] Knapp KE, Jester TL, Mihalik GB. Energy balances for photovoltaic modules: status and prospects. Proceedings of the 26th IEEE photovoltaic specialists conference 2000 p. 1450–5.
[23] Alsema EA, Frankl P, Kato K. Energy pay-back time of photovoltaic energy systems: present status and prospects. Proceedings of the 2nd world photovoltaic conference 1998 p. 2125–30.
[24] Nieuwlaar E, Alsema EA, editors. Environmental aspects of PV power systems, IEA PVPS Task 1 Workshop, Utrecht, The Netherlands, December; 1997.
[25] Sater BL, Goradia C. The high intensity solar cell—key to low cost photovoltaic power. Proceedings of the 11th IEEE photovoltaics specialists conference 1975 p. 356–63.
[26] White SW, Kulcinski GL. Birth to death analysis of the energy payback ratio and CO_2 gas emission rates from coal, fission, wind, and DT-fusion electrical power plants. Fusion Eng Des 2000;48(248):473–81.
[27] Hynes KM, Pearsall NM, Hill R. The sensitivity of energy requirements to process parameters for $CuInSe_2$ module production. 22nd IEEE PV specialists conference 1991 p. 822–7.
[28] Environmental resources management. A study into life cycle environmental impacts of photovoltaic technologies, Report ETSU S/P2/00240/REP prepared for the energy technology support unit (ETSU) on behalf of the department of trade and industry, UK; 1996.
[29] Bailey RL. Solar electrics: research and development. Ann Arbor, MI: Ann arbor science; 1980 p.118–9.
[30] Canada AH. Solar voltaic generator requirements for large-scale central-station. Proceedings of the 16th IEEE photovoltaic specialists conference 1982 p. 1081–86.
[31] Keoleian G, Lewis G. Application of life-cycle energy analysis to photovoltaic module design. Prog Photovoltaics 1997;5(4):287–300.
[32] Pick E, Wagner H-J. Cumulative energy demand (CED) and energy yield ratio (EYR) For wind energy converters. Proceedings of the world renewable energy congress VII 2002.
[33] Watt ME, Johnson AJ, Ellis M, Outhred HR. Life-cycle air emissions from PV power systems. Prog Photovoltaics 1998;6:127–36.

[34] Johnson AJ, Watt M, Ellis M, Outhred HR. Life cycle assessments of PV power systems for household energy supply. Environmental aspects of PV power systems, IEA PVPS Task 1 Workshop Utrecht, The Netherlands, December; 1997.

[35] Richards BS, Watt ME. Use of the energy yield ratio as a means of dispelling one myth of photovoltaics. Proceedings of Solar 2004: conference of ANZSES (Australian and New Zealand Solar Energy Society), 1–3 December 2004, Perth, Australia (in press).